Rapidity Dependence of Elliptic Flow from Hydrodynamics

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Outline

- Introduction
- Results so far
- T^{th} dependence of $v_2(\eta)$
- Initial condition from the CGC and its consequence
- Summary & discussion

Introduction

$v_2(y)$ is supposed to reflect global dynamics…

→ How obtain by hydrodynamics?

Non-central coll. → No cylindrical sym.

Non-Bjorken behavior → No scaling ansatz

High energy collisions (@RHIC) → No Cartesian coordinate?

Need **full** 3D hydro simulations in τ-η coordinate

T.H., PRC65,011901(2002).

From Experimental Point of View

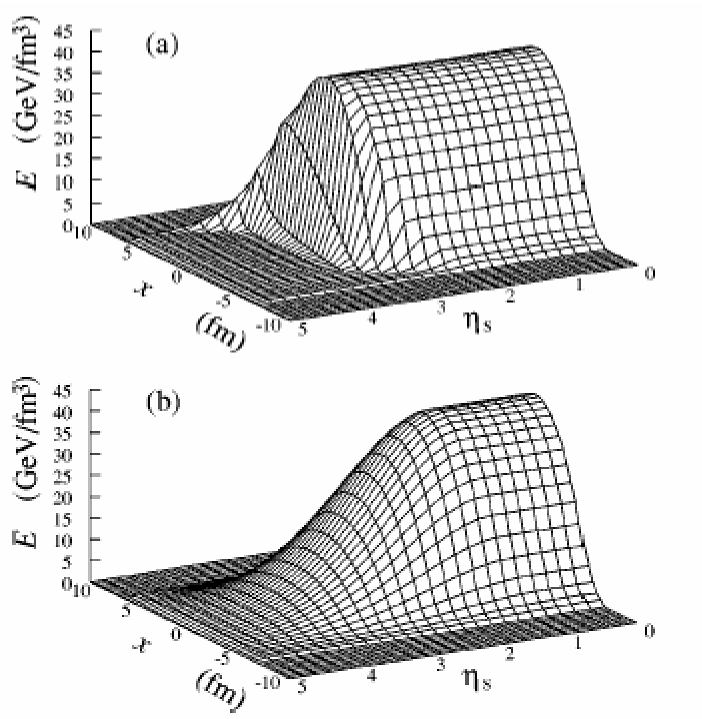
Need broad acceptance in longitudinal direction

See S.Manly's talk

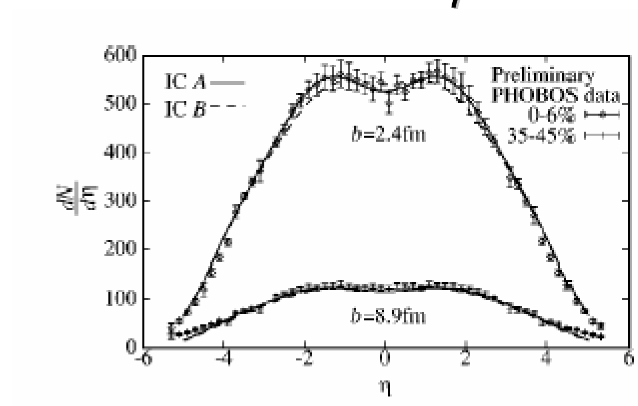
Results so far (1)

T.H., PRC65,011901(2002).

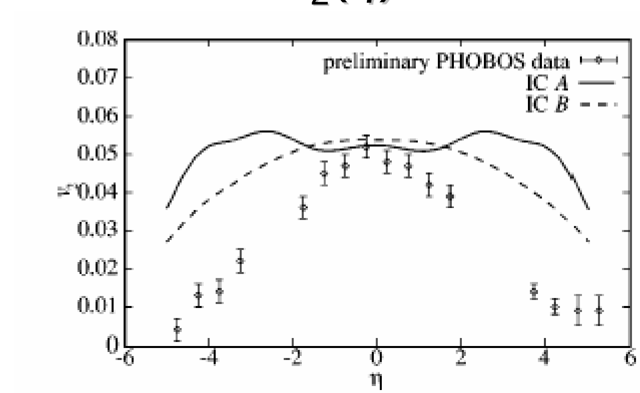
•The shape of $v_2(\eta)$ depends largely on initial longitudinal profile



$dN/d\eta$



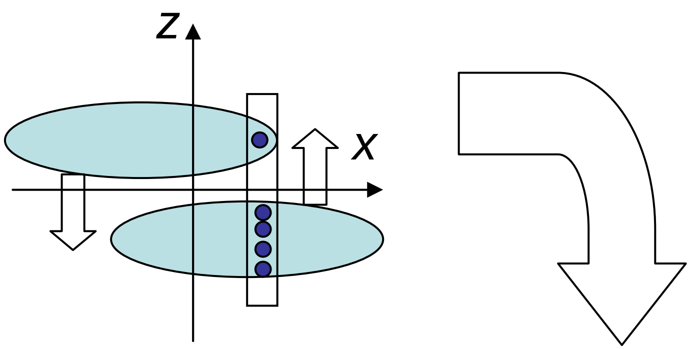
$v_2(\eta)$



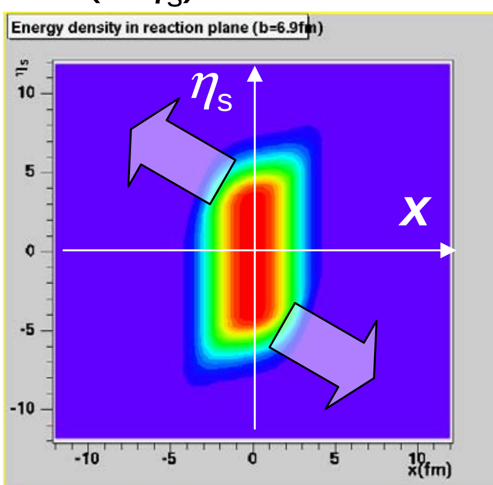
Local Rapidity Shift

- Local rapidity shift

(J.Sollfrank *et al*., Eur.Phys.J.C6,525(1999))



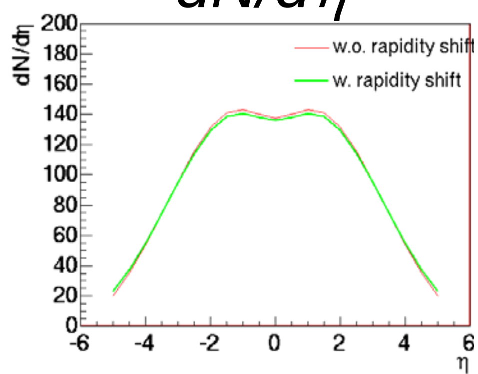
$E(x,\eta_s)$ at b=6.9fm



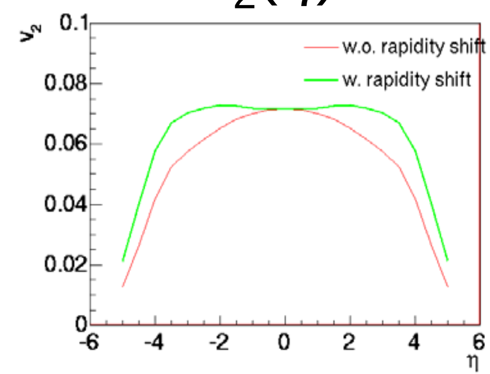
Third flow?
(L.P.Csernai and D.Rohrich, PL B458, 454(1999))

Direct charged, T^{th}=140MeV, b=6.9fm

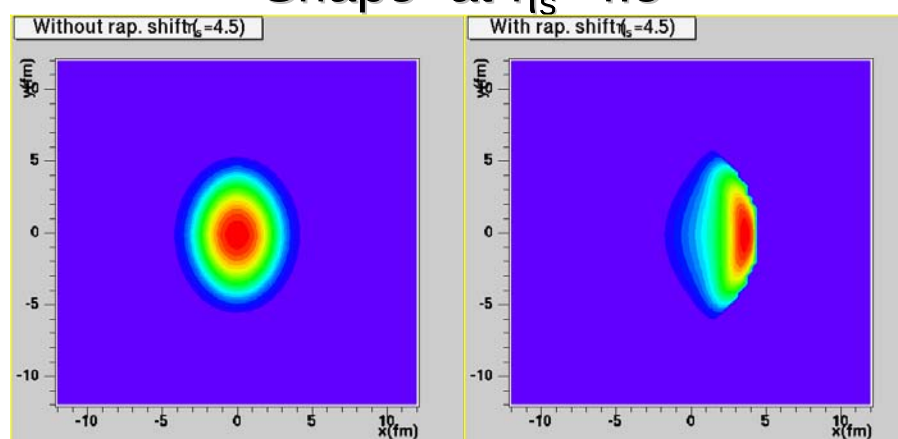
$dN/d\eta$



$v_2(\eta)$



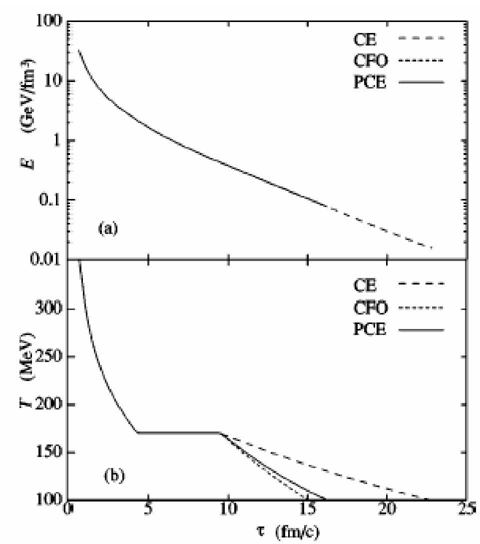
"Shape" at η_s=4.5

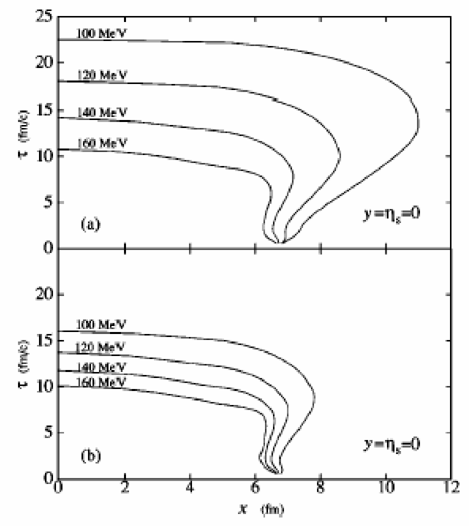


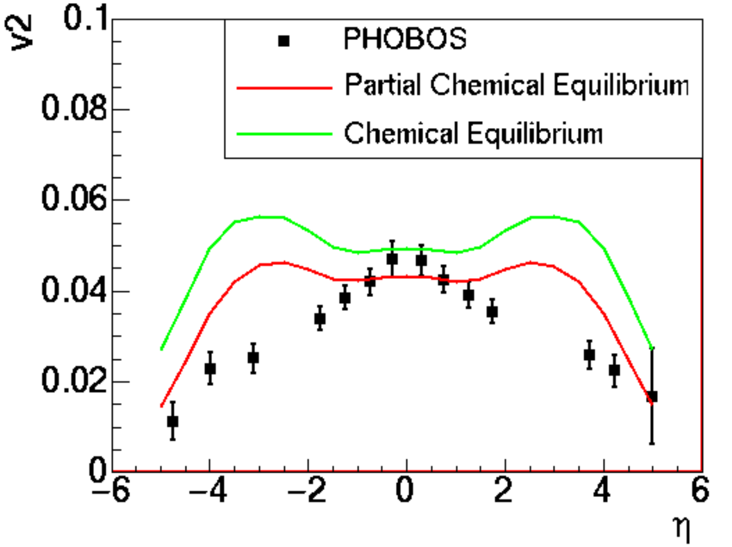
Results so far (2)

T.H. and K.Tsuda, PRC66,054905(2002).

- v_2 is reduced by chemical non-equilibrium property







- Space-time evolution is completely different from conventional (chemically equilibrated) EOS.

$v_2(\eta)$ and $v_2(y)$

P. Kolb, Heavy Ion Phys.**15**, 279(2002).

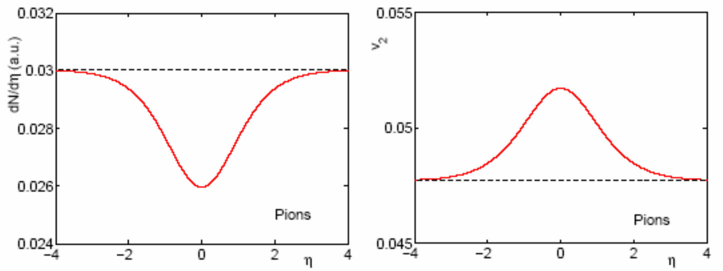
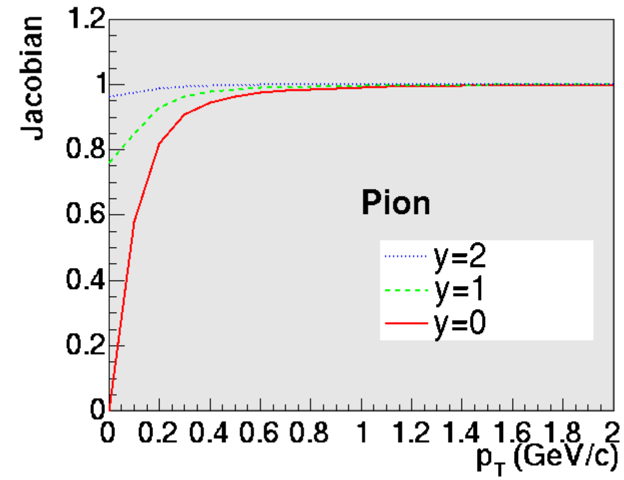


Fig. 6. Transformation of boost-invariant quantities (independent of rapdidity y) to pseudo-rapidity. The left plot shows the effect of the Jacobian of the transformation on the particle spectra, the right plot the influence on the elliptic flow coefficient v_2.

Jacobian as an weight fn.

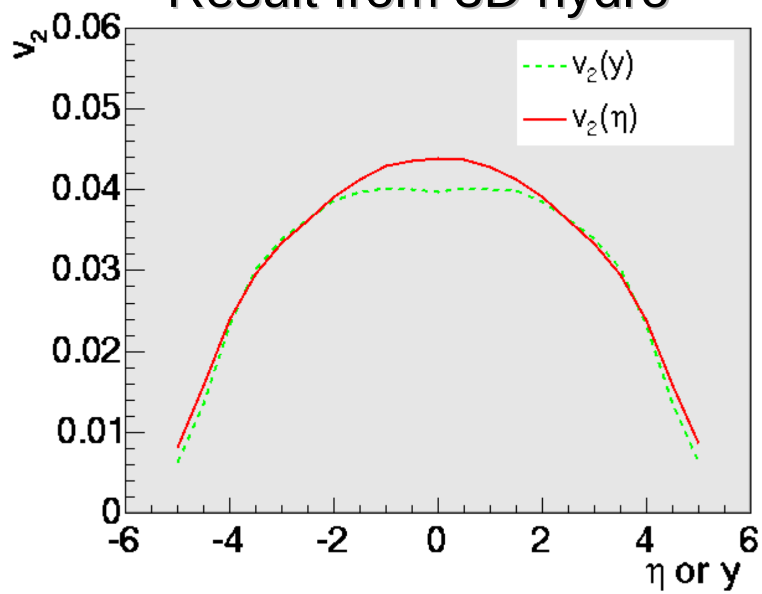


Jacobian between y and η

$$J = p/E = \sqrt{1 - \frac{m^2}{(p_T^2 + m^2)\cosh^2 y}}$$

$$\begin{aligned}\langle\cos(2\phi)\rangle &= \frac{\int d^2p_T \cos(2\phi)(dN/d^2p_T d\eta)}{\int d^2p_T (dN/d^2p_T d\eta)} \\ &= \frac{\int d^2p_T \cos(2\phi)(J \times dN/d^2p_T dy)}{\int d^2p_T (J \times dN/d^2p_T dy)}\end{aligned}$$

Result from 3D hydro

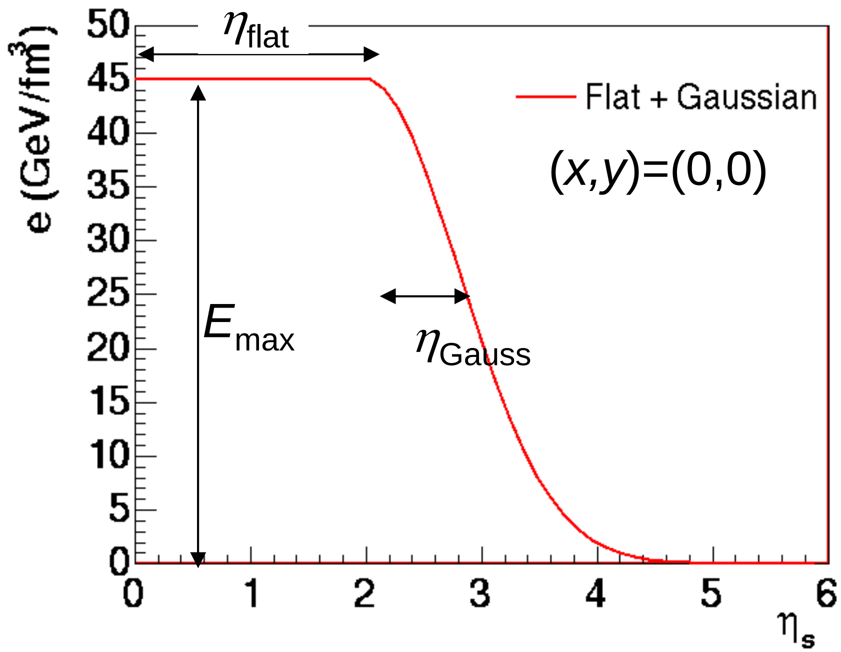


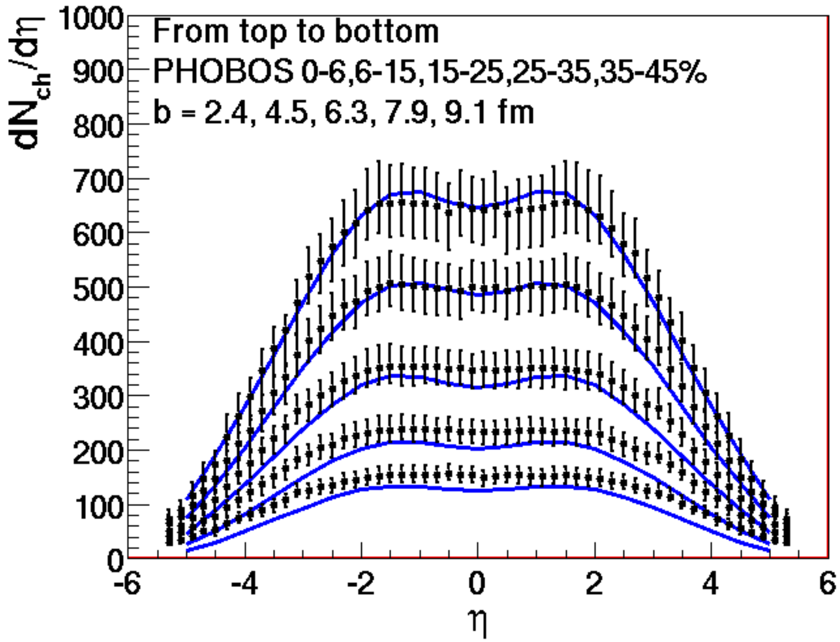
Summary (part 1)

- Ambiguity of init. condition.
  - → Smaller flat region would be good.
  - → No local rapidity shift
- Realistic EOS (chemically non-eq.)

Return game in 200 GeV collisions

Initial Condition in Long. Direction





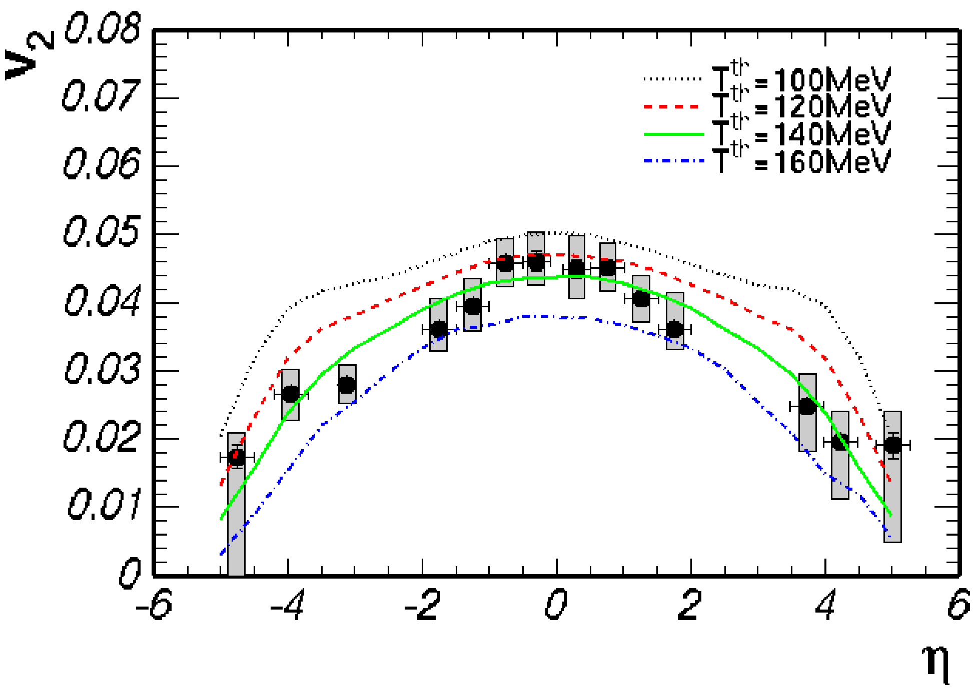
- E_{max}=45 GeV/fm^3
- η_{flat} = 2.0
- η_{Gauss} = 0.8

★ No local rapidity shift

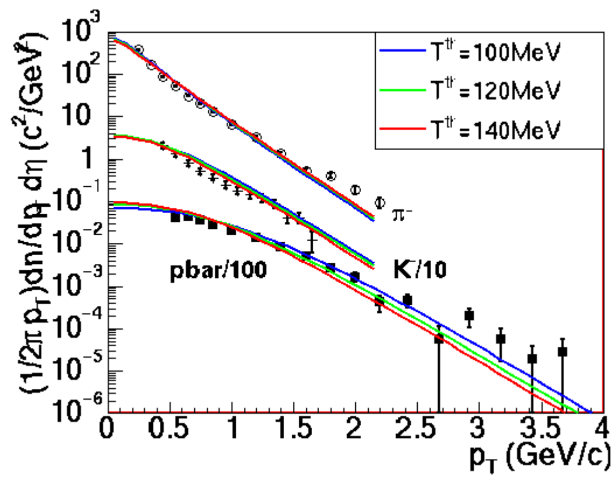
# of binary coll. scaling for finite b. Works well as centrality dep. for initial condition.

(P.Kolb *et al.*, Nucl.Phys.A696,197,(2001))

T^{th} Dependence of v_2



As far as pions, T^{th} is not determined by p_T slope within chemically non-equilibrium EOS model.



- v_2 glows also in hadron phase.
- Eventually, $v_2(y)$ becomes flat as T^{th} decreases

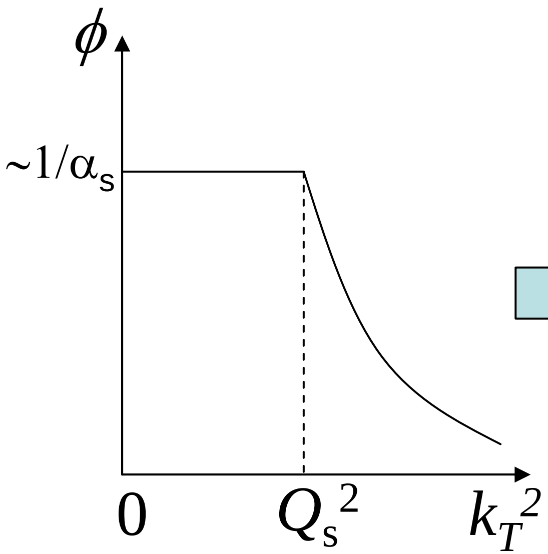
dN/dη from a Saturation Model

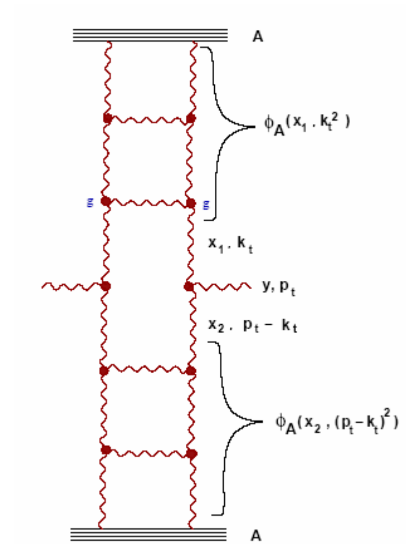
D. Kharzeev and E. Levin, Phys.Lett.B523,79(2001)

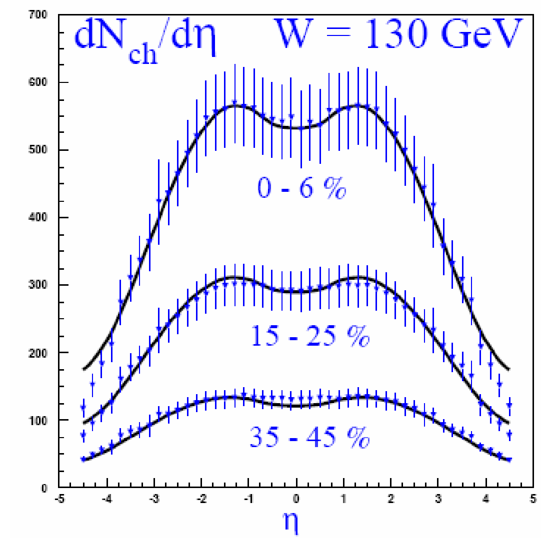
$$xG_A(x,Q^2) = \int^{Q^2} dk_T^2 \varphi_A(x,k_T^2)$$

gg→g

Parton-hadron duality







$$E\frac{d\sigma}{d^3p} = \frac{4\pi N_c}{N_c^2-1}\frac{1}{p_T^2}\int dk_T^2 \alpha_s \varphi_A(x_1,k_T^2)\varphi_A(x_2,(p-k)_T^2)$$

Initial Condition from CGC (hydrodynamic afterburner for CGC)

Saturation scale at a transverse position:

$$Q_s^2(x_\perp) = \frac{4\pi^2 N_c}{N_c^2 - 1}\alpha_s(Q_s^2)xG(x, Q_s^2)\frac{\rho_{\mathrm{part}}(x_\perp)}{2}$$

where

$$xG(x, Q^2) = K \ln\left(\frac{Q^2 + \Lambda^2}{\Lambda_{\mathrm{QCD}}^2}\right) x^{-\lambda}(1-x)^n$$

K=0.7
κ^2=0.94 (T^{th}=100MeV)
λ=0.2

Unintegrated gluon distribution can be written

$$\phi(x, k_T^2) = \begin{cases} \frac{\kappa}{\alpha_s(Q_s^2)}\frac{Q_s^2}{Q_s^2+\Lambda^2}, & k_T \le Q_s(x), \\ \frac{\kappa}{\alpha_s(Q_s^2)}\frac{Q_s^2}{k_T^2+\Lambda^2}, & k_T > Q_s(x). \end{cases}$$

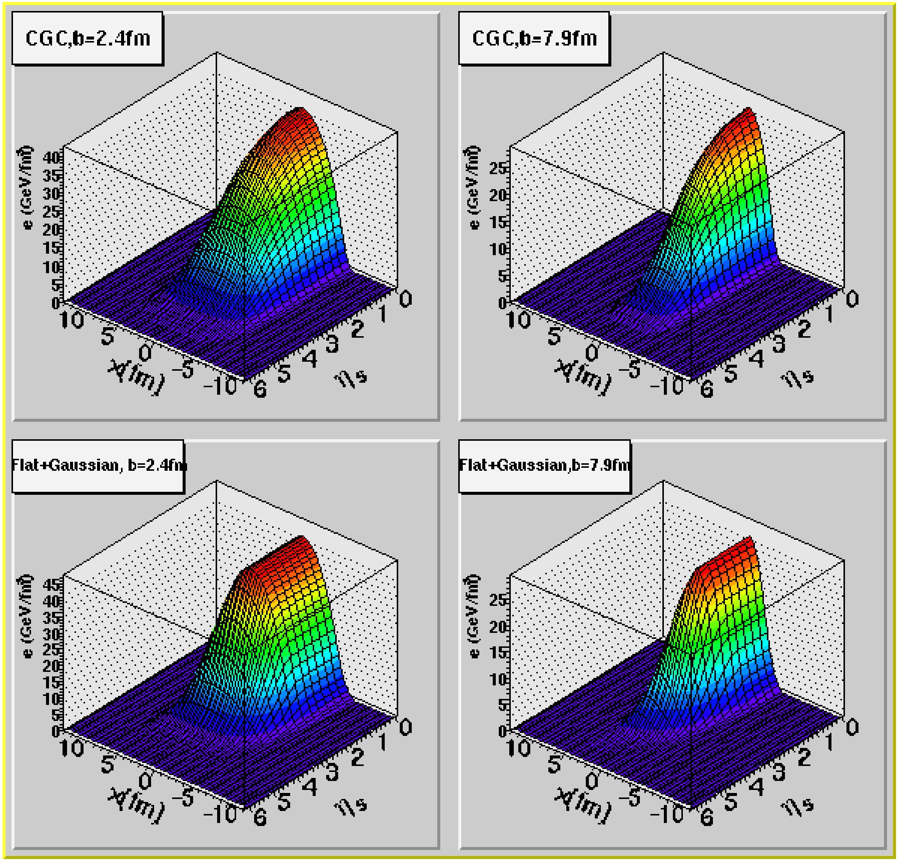
$$\boxed{\frac{dE_g}{d^2x_\perp dy} = \frac{4N_c}{N_c^2-1}\int p_T \frac{d^2p_T}{p_T^2}\int d^2k_T \alpha_s \varphi_A(x_1, k_T^2; x_\perp)\varphi_A(x_2, (p-k)_T^2; x_\perp)}$$

Momentum rapidity *y* → space time rapidity η_s

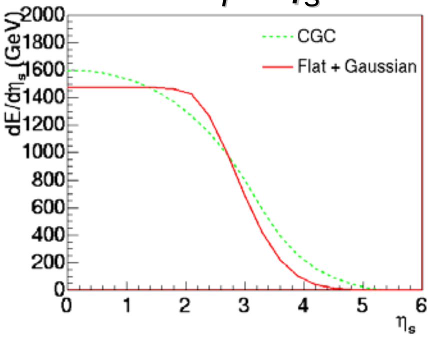
$$e(\tau_0, \vec{x}) = \frac{dE_g}{\tau_0 d\eta_s dx_\perp^2}$$

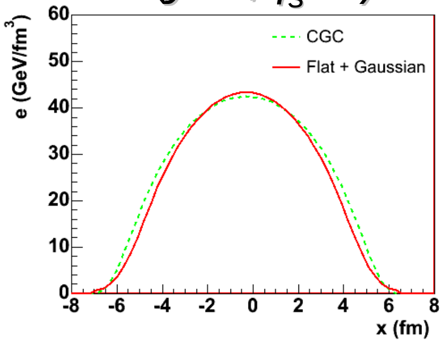
Input for hydrodynamics
"CGC + Hydro (+ Jet) model"

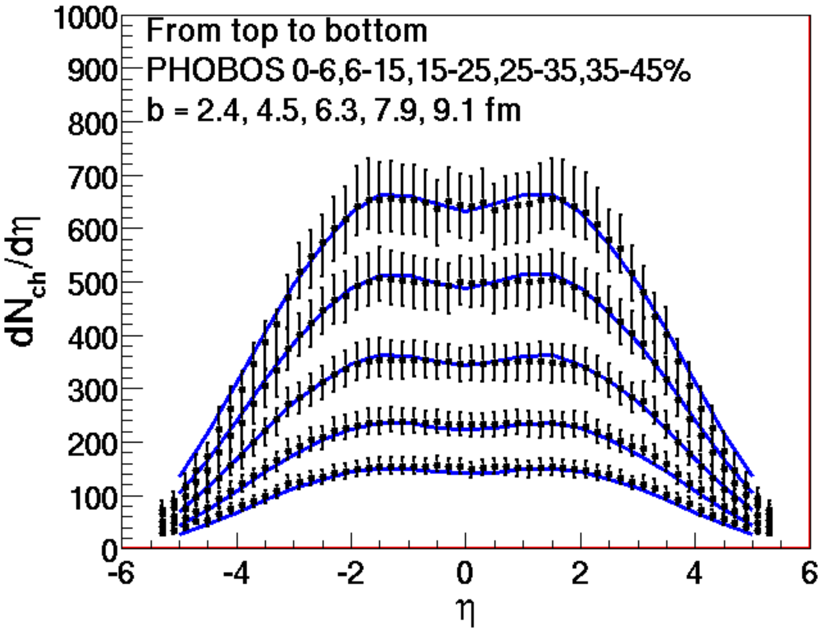
Initial Energy Density Distribution and $dN_{ch}/d\eta$



b=2.4fm

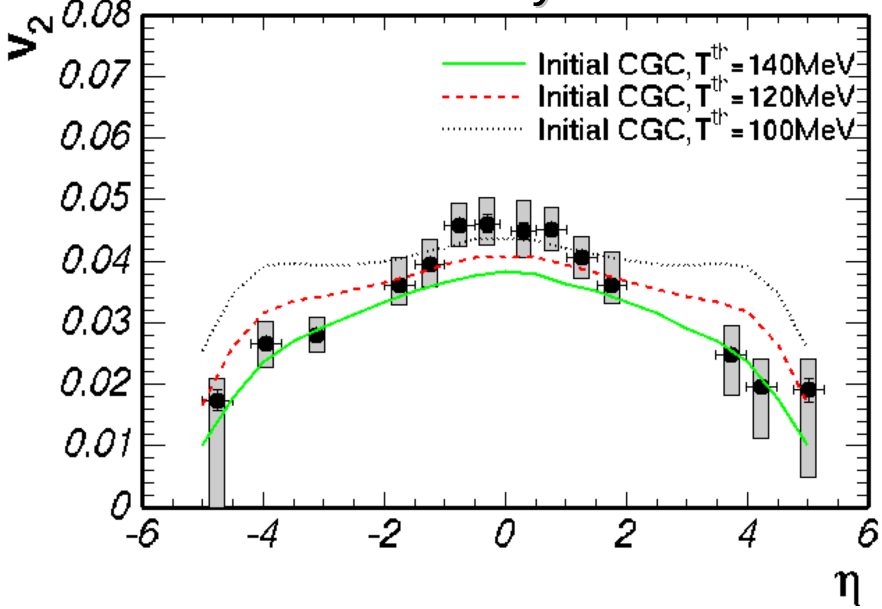




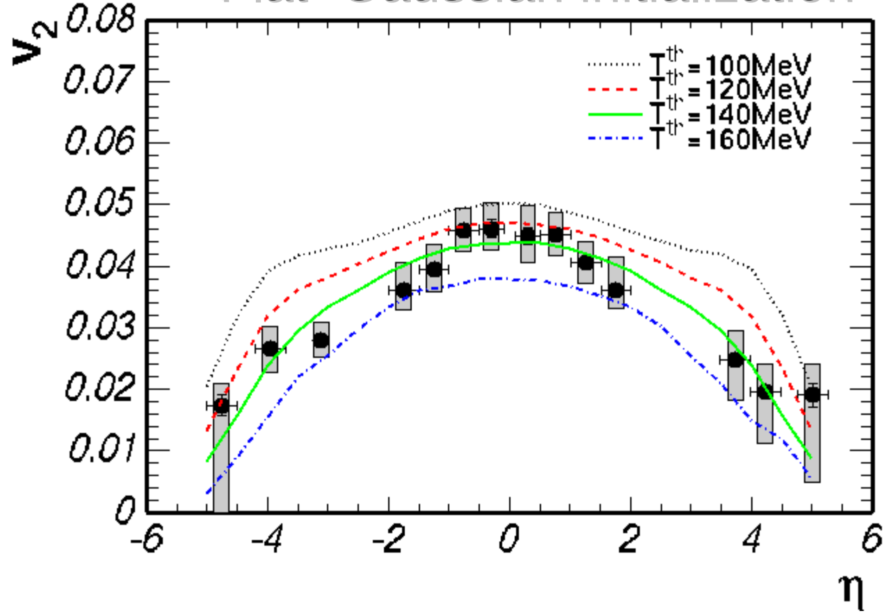


$v_2(\eta)$ from CGC+Hydro

CGC+Hydro



Flat+Gaussian initialization



- Slightly suppressed near midrapidity region
  - Pressure gradient in longitudinal direction
  - Pressure gradient in transverse direction

  →Stronger longitudinal flow and weaker transverse flow in CGC+hydro case than in flat+Gaussian case.

Summary & Discussion

- There IS a solution for $v_2(\eta)$ from hydrodynamics.
- Further systematic studies are needed.
  - Initial condition? T^{th} dependence ? EOS ?
- CGC+hydro(+jet) model ("Improvement" of I.C.)

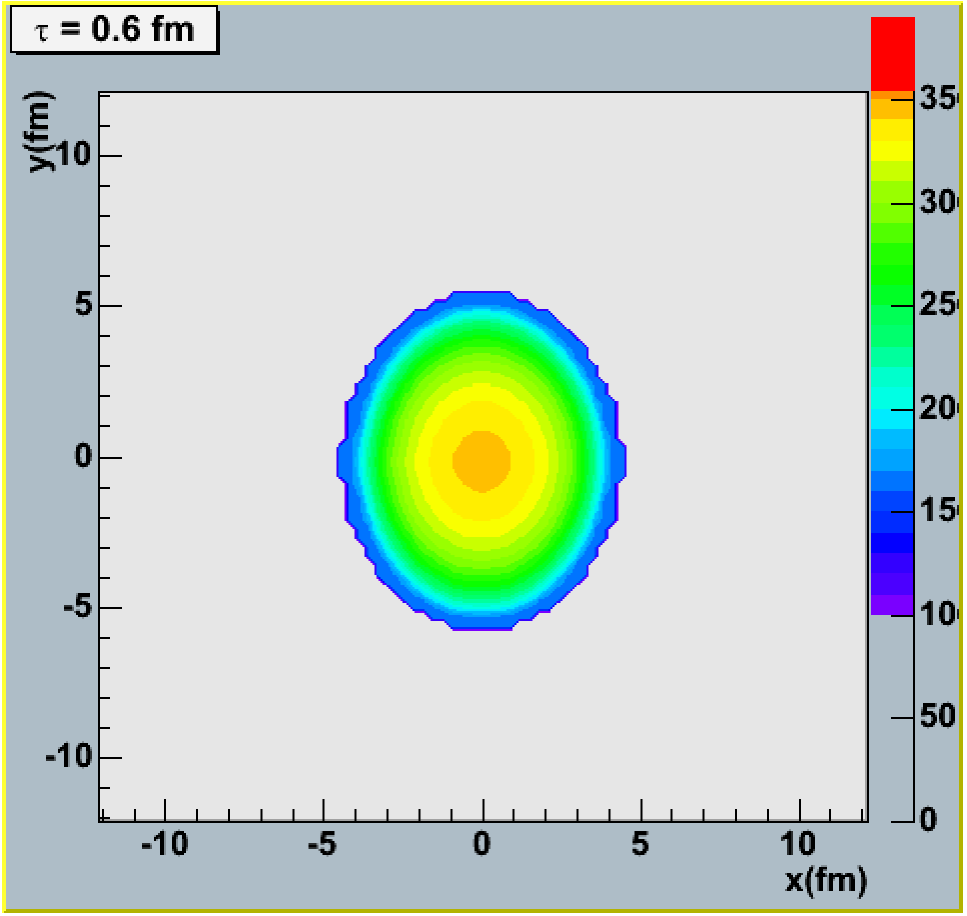
- Consistency check

→ $\langle p_T \rangle(y)$ & p_T spectra in forward rapidity (BRAHMS data)

→ $v_2(p_T)$ @ forward rapidity region ?

→ $v_1(y)$??? ←third flow components ?

Thank you!

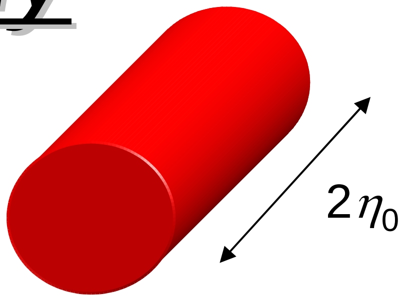


CGC+hydro at b=6.9fm in transverse plane

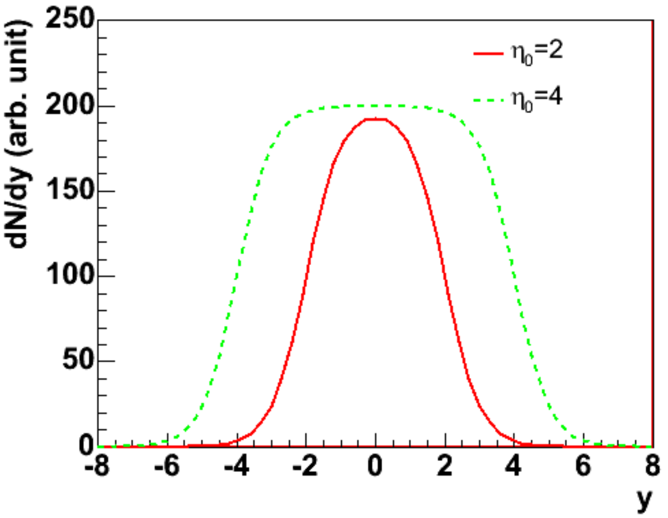
Flat Energy $\neq$ Flat dN/dy

Basic assumption

1. Finite Bjorken rod ($-\eta_0<\eta_s<\eta_0$)
2. Massless pions
3. Constant T and Boltzmann approximation



$$\begin{aligned}
\frac{dN}{dY} &\propto \pi R^2 \int_{-\eta_0}^{\eta_0} d\eta_s \int_0^{\infty} p_T dp_T \exp(-p_T \cosh(\eta_s - Y)/T) \\
&= \pi R^2 \int_{-\eta_0}^{\eta_0} d\eta_s \frac{T^2}{\cosh^2(\eta_s - Y)} \\
&= \pi R^2 T^2 \int_{\tanh(-\eta_0 - Y)}^{\tanh(\eta_0 - Y)} dx \\
&= \pi R^2 T^2 (\tanh(Y+\eta_0) - \tanh(Y-\eta_0))
\end{aligned}$$



Accepted Events by PHOBOS

Not minimus bias!

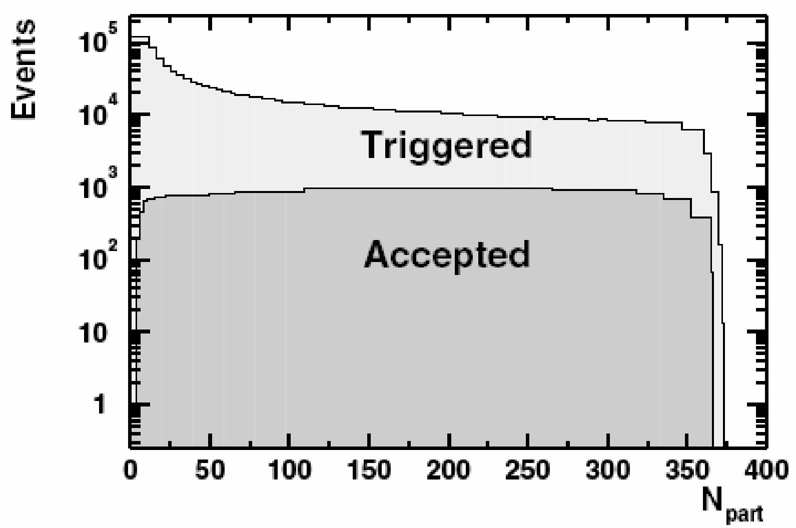
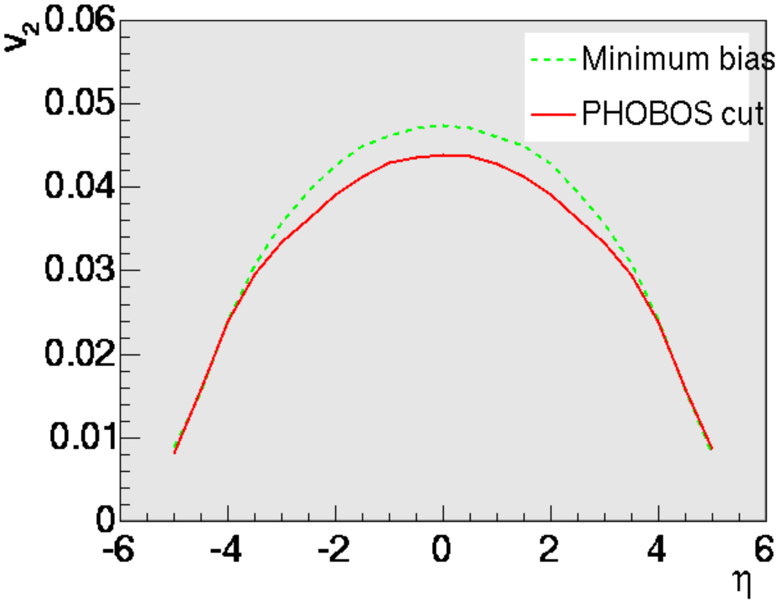


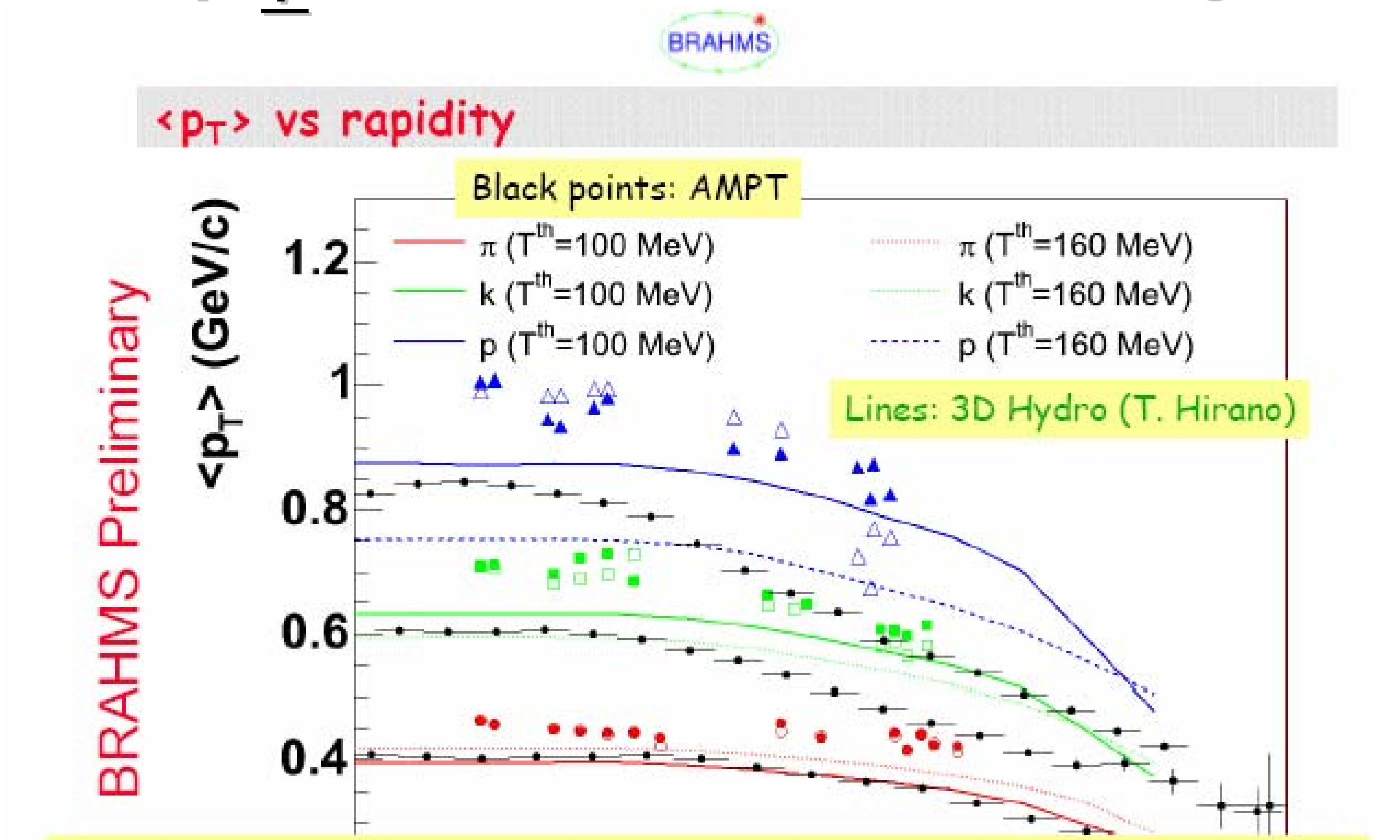
FIG. 1. The event distribution as a function of $N_{\rm part}$ for triggered events (upper curve) and for data accepted for use in the final analysis (lower curve).

B.B.Back et al.(PHOBOS), PRL89,222301(2002).



In hydro, average over N_{part} in multiples of 25 up to 325.

Mean p_T as a Function of y



- AMPT (HIJING + Re-scattering) shows stronger y dependence then data
- 3D-Hydro describe y-dependence of data with a single T_{th} value at~< 100 MeV (initial condition is tuned for dN/dη and T_{ch} = 170 MeV)
- Strong Radial Flow in 0< y<~3 (Blast-Wave Fit gives T~120 MeV β~0.6 at y=0)

J.H.Lee(BRAHMS), talk at Forward Physics at RHIC, Oct.9, 2003,BNL

Blast Wave Fit in Forward Rapidity Region by BRAHMS

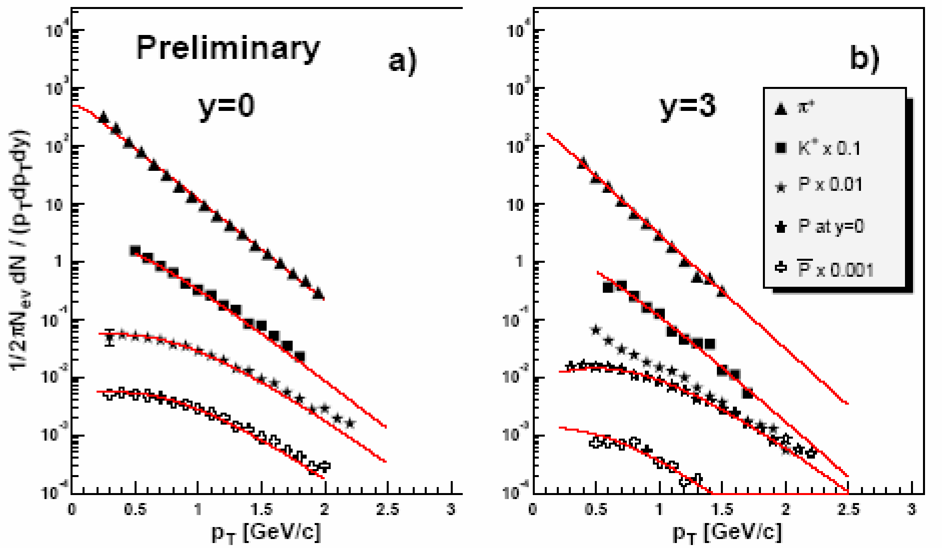


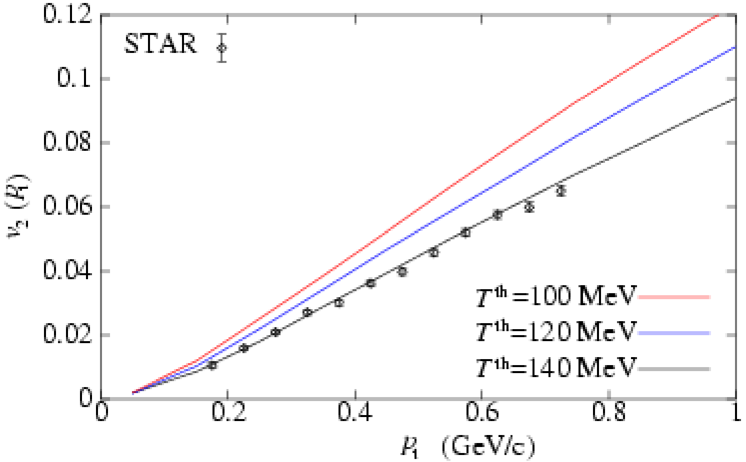
FIGURE 2. "Blast wave" fits to pions, kaons and protons at rapidity y=0 (panel a) and y=3 (panel b)

TABLE 1. Results of blast wave fits

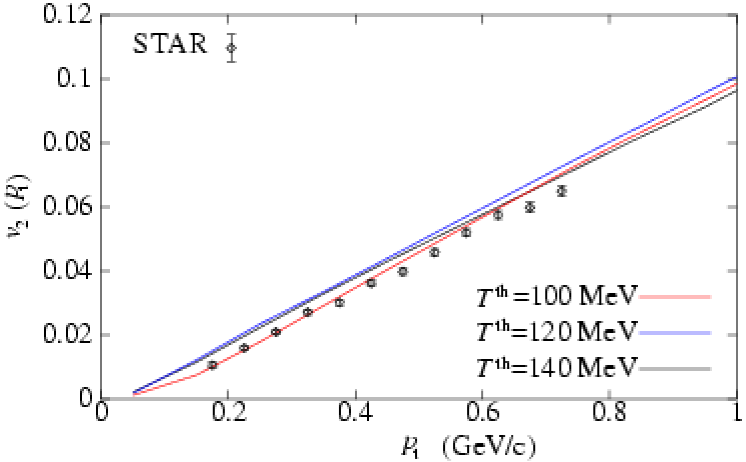
Rapidity	Temperature [MeV]	Velocity
0	127 ± 2	0.57 ± 0.01
0.7	112 ± 1	0.60 ± 0.01
2.2	128 ± 3	0.50 ± 0.01
3	136 ± 4	0.44 ± 0.02

R.Debbie (BRAHMS), proceeding for The 8th Conference on Intersections of Particle And Nuclear Physics (CIPANP2003), New York City, New York (May 19-24, 2003).

$v_2(p_T)$ @ 130AGeV



Chemical non-eq. model



Chemical eq. model

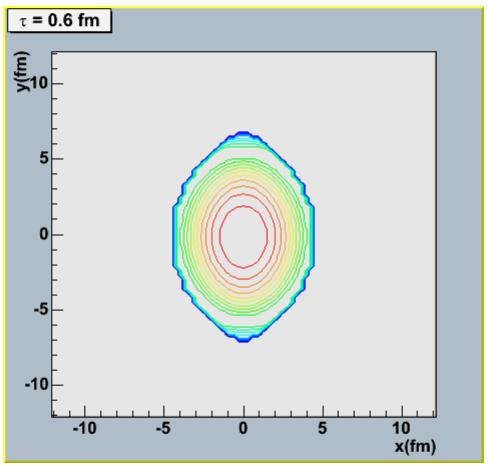
Table. T^{th} dependence for pions

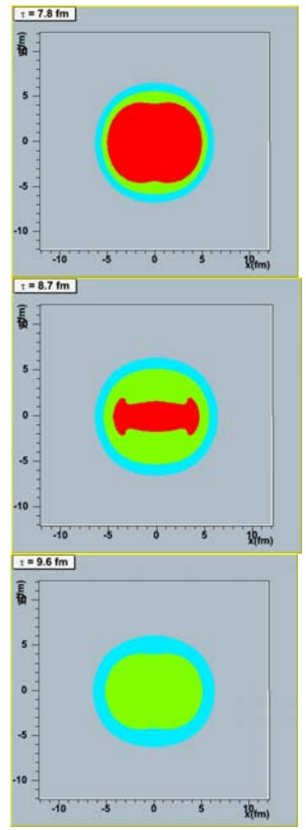
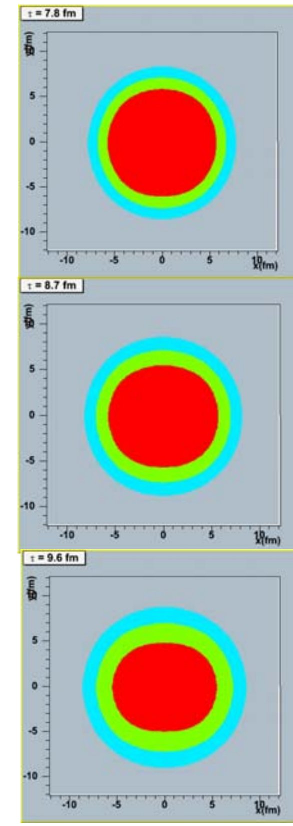
	p_T slope	$v_2(p_T)$
Chem. eq.	yes	no
Chem. non-eq.	no	yes

Freezeout Hypersurface

100-120MeV
120-140MeV
140- MeV

Initial temperature (b=6.9fm)

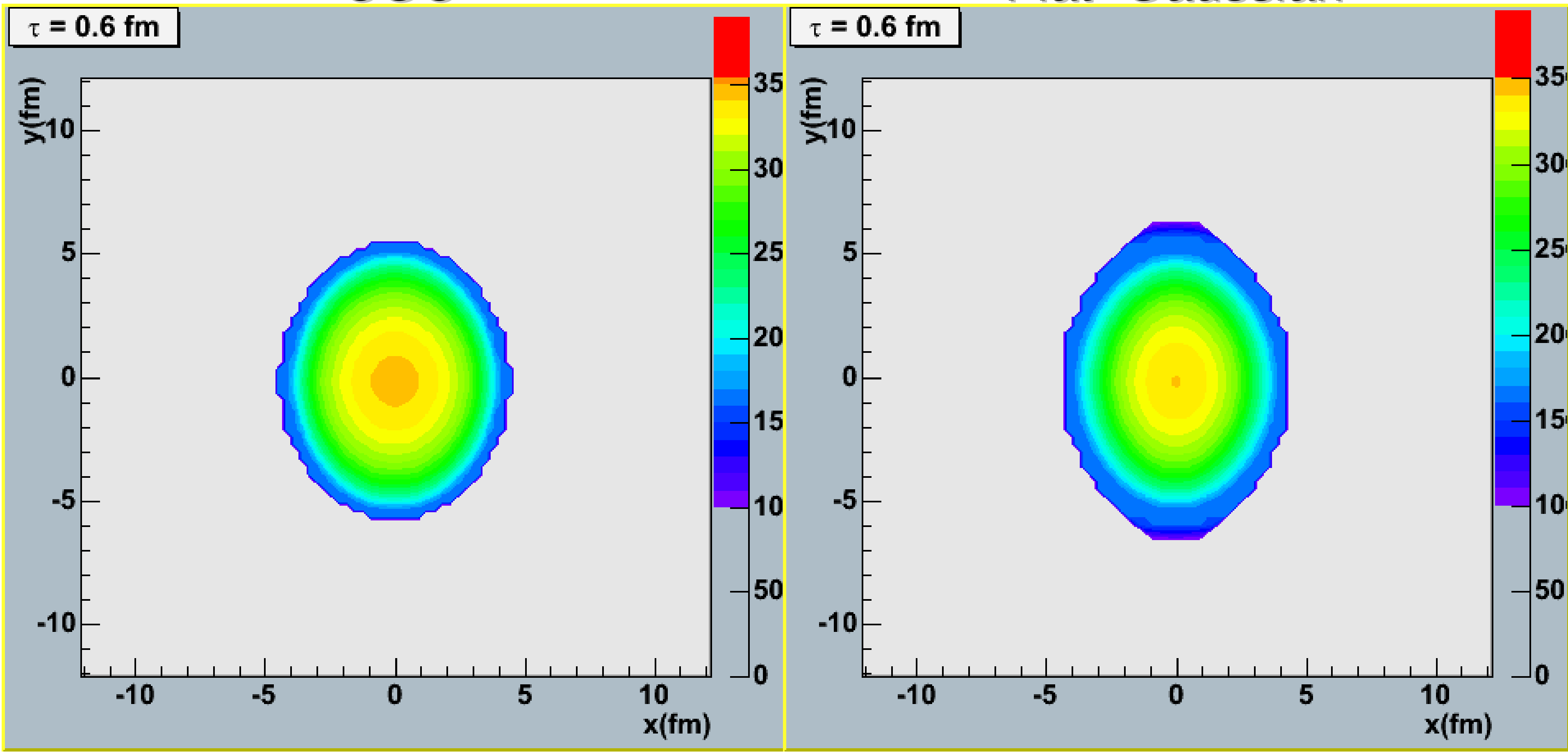


PCE	tau (fm)	CE
	7.8	
	8.7	
	9.6	

Movie

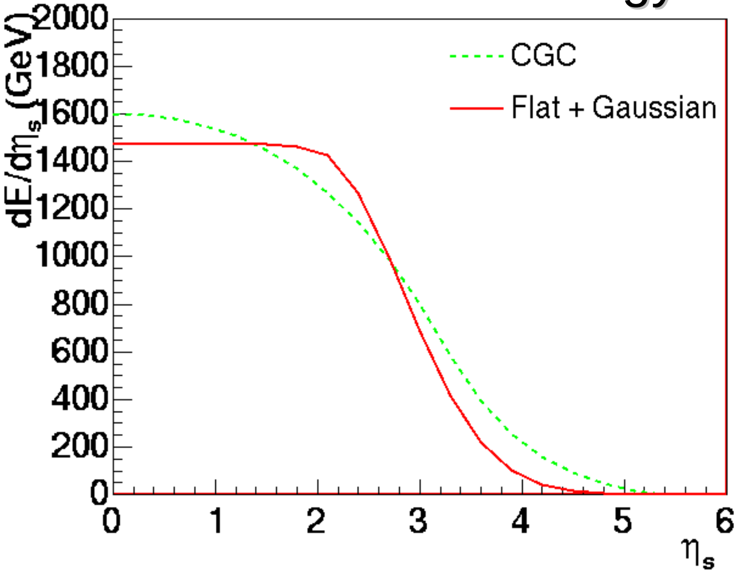
CGC

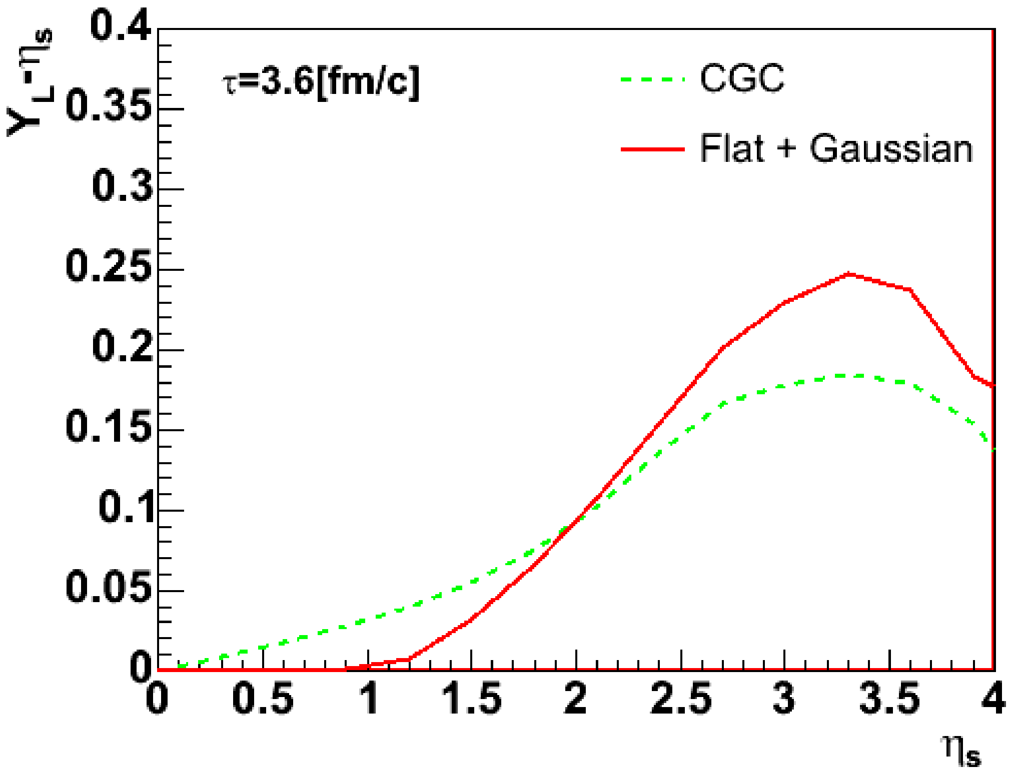
Flat+Gaussian



Longitudinal Acceleration

Initial transverse energy





Y_L-η_s: Deviation from scaling flow